Screw instability of the magnetic field connecting a rotating black hole with its surrounding disk

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ABSTRACT

Screw instability of the magnetic field connecting a rotating black hole (BH) with its surrounding disk is discussed based on the model of the coexistence of the Blandford-Znajek (BZ) process and the magnetic coupling (MC) process (CEBZMC). A criterion for the screw instability with the state of CEBZMC is derived based on the calculations of the poloidal and toroidal components of the magnetic field on the disk. It is shown by the criterion that the screw instability will occur, if the BH spin and the power-law index for the variation of the magnetic field on the disk are greater than some critical values. It turns out that the instability occurs outside some critical radii on the disk. It is argued that the state of CEBZMC always accompanies the screw instability. In addtition, we show that the screw instability contributes only a small fraction of magnetic extraction of energy from a rotating BH.

Subject headings: accretion, accretion disk — black hole physics — magnetic fields — instability

1. INTRODUCTION

It is well known that the magnetic field configurations with both poloidal and toroidal components can be screw instable (Kadomtsev 1966; Bateman 1978). According to the Kruskal-Shafranov criterion (Kadomtsev 1966), the screw instability will occur, if the toroidal magnetic field becomes so strong that the magnetic field line turns around itself about once. Recently some authors discussed the screw instability in black hole (BH) magnetosphere. Gruzinov (1999) argued that a Kerr BH, being connected with a disk by a bunch of closed field lines, can flare quasi-periodically, and this process can be regarded as a new mechanism for extracting rotational energy from the BH. Li (2000a) discussed the screw instability of the magnetic field in the Blandford-Znajek (BZ) process (Blandford & Znajek 1977), which results in a stringent upper bound to the BZ power. Tomimatsu et el. (2001) studied the condition of the screw instability in the framework of the variation principle, and argued that the field-line rotation has a stabilizing effect against the screw instability.

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Recently much attention has been paid on the magnetic coupling (MC) process, where energy and angular momentum are extracted from a fast-rotating BH to its surrounding disk by virtue of closed magnetic field lines (Blandford 1999; Li 2000b, 2002a; Wang, Xiao & Lei 2002, hereafter WXL; Wang, Lei & Ma 2003, hereafter WLM). The MC process can be used to explain a very steep emissivity in the inner region of the disk, which is found by the recent *XMM-Newton* observation of the nearby bright Seyfert 1 galaxy MCG-6-30-15 (Wilms et al. 2001; Li 2002b; WLM). Compared with the BZ process, the disk load in the MC process is much better understood than the remote load. Very recently we discussed the condition for the coexistence of the BZ and MC processes (CEBZMC), and some electromagnetic quantities, such as electric field, magnetic field and electric current in the BH magnetosphere, are determined (Wang et al. 2003, hereafter WMLY).

The above works motivate us to discuss the screw instability in CEBZMC based on the Kruskal-Shafranov criterion and our calculations of the poloidal and toroidal components of the magnetic field. This paper is organized as follows. In §2 we give a brief description on our model of CEBZMC. In §3 the criterion of the screw instability is derived based on the Kruskal-Shafranov criterion and our calculations of the poloidal and toroidal components of the magnetic field on the disk. It turns out that the screw instability is related intimately to the two parameters, i.e., the BH spin and the power-law index for the variation of the magnetic field on the disk. In addition, the correlation of the screw instability with CEBZMC is discussed. It is shown that the state of CEBZMC always accompanies the screw instability, and the region of the screw instability can be determined by the criterion for the given values of the BH spin and the power-law index. In §4 we discuss the effect of the screw instability on magnetic extraction of energy from the rotating BH. It is shown that the screw instability contributes only a small fraction of magnetic extraction of energy from a rotating BH. Finally, in §5, we summarize our main results.

Throughout this paper the geometric units $G = c = 1$ are used.

2. DESCRIPTION OF THE MODEL OF CEBZMC

Considering that the remote load in the BZ process and the load disk in the MC process are connected with a rotating BH by open and closed magnetic field lines, respectively, we studied a model of CEBZMC (WXL, WMLY). The poloidal configuration of the magnetic field is shown in Figure 1, where r_{in} and r_{out} are the radii of the inner and outer boundaries of the MC region, respectively. The angle θ_M indicates the angular boundary between the open and closed field lines on the horizon, and θ_L is the lower boundary angle for the closed field lines. The angles θ_M and θ_L are connected with r_{out} and r_{in} by the highest and the lowest closed field lines, respectively. Throughout this paper $\theta_L = 0.45\pi$ is assumed in calculation. Following Blandford (1976), we assume that the poloidal magnetic field B_D^p on the disk varies with the radial coordinate ξ as a power law,

$$B_D^p \propto \xi^{-n}, \tag{1}$$

Hereafter the subscript "D" is used to indicate the quantities on the disk. The parameter n is the power-law index and $\xi \equiv r/r_{ms}$ is the radial coordinate on the disk, which is defined in terms of the radius $r_{ms} \equiv M\chi_{ms}^2$ of the marginally stable orbit (Novikov & Thorne 1973).

An equivalent circuit for the BZ and MC processes is used as shown in Figure 2, in which the symbols have the same meanings as given in WXL.

A stationary, axisymmetric magnetosphere anchored in a Kerr BH and its surrounding disk can be described in Boyer-Lindquist coordinates, and the concerned metric parameters are given as follows (MacDonald and Thorne 1982, hereafter MT).

$$\left.\begin{array}{ll}\Sigma^2 = \left(r^2 + a^2\right)^2 - a^2 \Delta \sin^2\theta, & \rho^2 = r^2 + a^2\cos^2\theta, \\ \Delta = r^2 + a^2 - 2Mr, & \varpi = (\Sigma/\rho)\sin\theta.\end{array}\right\}, \tag{2}$$

where M and $a \equiv J/M$ are the mass and the specific angular momentum of a Kerr BH, respectively. The current in each loop of the equivalent circuit for the BZ and MC processes is expressed by

$$I_i = \frac{\Delta\varepsilon_{Hi} + \Delta\varepsilon_{Li}}{\Delta Z_{Hi} + \Delta Z_{Li}} = \left(\Delta\Psi_i/2\pi\right)\frac{\Omega^H - \Omega_i^F}{\Delta Z_{Hi}}, \tag{3}$$

where the quantities in equation (3) have the same meaning as given in WXL. In WMLY we derived the poloidal currents on the horizon as follows.

$$I_{H,BZ}^p\left(a_*;\theta,n\right) = I_0\frac{a_*\left(1-k\right)}{2\csc^2\theta - \left(1-q\right)}, \quad 0 < \theta < \theta_M, \tag{4}$$

$$I_{H,MC}^p\left(a_*;\theta,n\right) = I_0\frac{a_*\left(1-\beta\right)}{2\csc^2\theta - \left(1-q\right)}, \quad \theta_M < \theta < \theta_L, \tag{5}$$

$$I_0 \equiv B_H^p M \approx B_4\left(M/M_\odot\right) \times 1.48 \times 10^{10} A, \tag{6}$$

where the subscripts "BZ" and "MC" represent the quantities involving the BZ and MC processes, respectively, and B_4 is the strength of the magnetic field in units of 10^4 G. In equations (4) and (5) the parameter $a_* \equiv a/M$ is the BH spin, and the parameter q is defined as $q = \sqrt{1-a_*^2}$. The quantity B_H^p is the poloidal component of the magnetic field on the horizon. Hereafter the subscript "H" is used to indicate the quantities on the horizon.

The parameters k and β are the ratios of the angular velocity of the open and closed magnetic field lines to that of the BH, respectively. Usually, $k = 0.5$ is taken for the optimal BZ power, while β depends on the BH spin a_* and ξ. Since the closed field lines are frozen in the disk, β is expressed by

$$\beta \equiv \Omega_D/\Omega_H = \frac{2\left(1+q\right)}{a_*}\left[\left(\sqrt{\xi}\chi_{ms}\right)^3 + a_*\right]^{-1}, \tag{7}$$

where Ω_H and Ω_D are the angular velocities of the BH and the disk, respectively.

The poloidal current flowing on the disk is equal to that flowing on the horizon in the same loop of Figure 2, i.e.,

$$I_{D,MC}^p\left(a_*;\xi,n\right) = I_{H,MC}^p = I_0\frac{a_*\left(1-\beta\right)}{2\csc^2\theta - \left(1-q\right)}, \quad 1 < \xi < \xi_{out}, \tag{8}$$

where ξ is related to the angular coordinate θ on the horizon by the mapping relation given in WMLY,

$$\cos\theta - \cos\theta_L = \int_1^{\xi} \mathrm{G}\left(a_*;\xi,n\right) d\xi, \tag{9}$$

where

$$\mathrm{G}\left(a_*;\xi,n\right) = \frac{\xi^{1-n}\chi_{ms}^2\sqrt{1+a_*^2\chi_{ms}^{-4}\xi^{-2}+2a_*^2\chi_{ms}^{-6}\xi^{-3}}}{2\sqrt{\left(1+a_*^2\chi_{ms}^{-4}+2a_*^2\chi_{ms}^{-6}\right)\left(1-2\chi_{ms}^{-2}\xi^{-1}+a_*^2\chi_{ms}^{-4}\xi^{-2}\right)}}. \tag{10}$$

The condition for CEBZMC is discussed in WMLY based on the following assumptions:

(1) The theory of a stationary, axisymmetric magnetosphere anchored in the BH and its surrounding disk formulated in MT is applicable not only to the BZ process but also to the MC process. The magnetosphere is assumed to be force-free outside the BH and the disk.

(2) The disk is both stable and perfectly conducting, and the closed magnetic field lines are frozen in the disk. The disk is thin and Keplerian, lies in the equatorial plane of the BH with the inner boundary being at the marginally stable orbit.

(3) The magnetic field is assumed to be constant on the horizon, and to vary as a power law with the radial coordinate of the disk as given by equation (1).

(4) The magnetic flux connecting a BH with its surrounding disk takes precedence over that connecting the BH with the remote load.

It is found that the state of CEBZMC will occur, provided that the BH spin a_* and the power-law index n are greater than some critical values. In the following sections we adopt the above assumptions to discuss the screw instability.

3. CRITERIOR OF SCREW INSTABILITY IN CEBZMC

3.1. Derivation of Criterion

According to the the Kruskal-Shafranov criterion, the screw instability will occur, if the magnetic field line turns around itself about once, i.e.,

$$\left(2\pi\varpi_D/L\right) B_D^p/B_D^T < 1, \tag{11}$$

where B_D^p and B_D^T are the poloidal and toroidal components of the magnetic field on the disk, respectively, and ϖ_D is the cylindrical radius on the disk and reads

$$\varpi_D = \Sigma_D/\rho_D = \xi M\chi_{ms}^2\sqrt{1+a_*^2\xi^{-2}\chi_{ms}^{-4}+2a_*^2\xi^{-3}\chi_{ms}^{-6}}. \tag{12}$$

In deriving equation (12) the Kerr metric parameters given in equation (2) are used. The quantity L

in equation (11) is the poloidal length of the closed field line connecting the BH with the disk. The criterion (11) can be rewritten as

$$B_D^p / B_D^T = \left(B_D^p / B_H^p \right) \left(B_H^p / B_D^T \right) < L / (2\pi \varpi_D). \tag{13}$$

Considering the continuum of magnetic flux between the two adjacent magnetic surfaces connecting the BH and the disk, we have

$$B_H^p 2\pi \left(\varpi\rho \right)_{r=r_H} d\theta = -B_D^p 2\pi \left(\varpi\rho \Big/ \sqrt{\Delta} \right)_{\theta=\pi/2} dr. \tag{14}$$

Incorporating equation (14) with the mapping relation in WMLY, we express the ratio B_D^p / B_H^p as

$$\frac{B_D^p}{B_H^p} = \frac{2\left(1+q\right)\sqrt{1 + a_*^2 \xi^{-2} \chi_{ms}^{-4} - 2\xi^{-1}\chi_{ms}^{-2}}}{\xi \chi_{ms}^4 \sqrt{1 + a_*^2 \xi^{-2} \chi_{ms}^{-4} + 2a_*^2 \xi^{-3} \chi_{ms}^{-6}}} \mathrm{G}\left(a_*; \xi, n\right). \tag{15}$$

The ratio B_H^p / B_D^T can be calculated by using equation (8), and the radial current density flowing on the disk can be written as

$$j_D^p \left(a_*; \xi, n\right) = I_{D,MC}^p \left(a_*; \xi, n\right) / (2\pi \varpi_D). \tag{16}$$

By using Ampere's law the toroidal magnetic field $\mathbf{B}_D^T$ on the disk is expressed by

$$\mathbf{B}_D^T = 4\pi \mathbf{j}_D^p \times \mathbf{n}, \tag{17}$$

where $\mathbf{n}$ is the unit vector normal to the disk. Incorporating equations (8), (12), (16) and (17), we have

$$\frac{B_H^p}{B_D^T} = \frac{\xi \chi_{ms}^2 \sqrt{1 + a_*^2 \xi^{-2} \chi_{ms}^{-4} + 2a_*^2 \xi^{-3} \chi_{ms}^{-6}} \left[2\csc^2\theta - (1-q)\right]}{2a_* \left(1-\beta\right)}. \tag{18}$$

Substituting equations (15) and (18) into the criterion (13), we have

$$\left(2\pi \varpi_D / L\right) F\left(a_*; \xi, n\right) < 1, \tag{19}$$

where

$$F\left(a_*; \xi, n\right) = \frac{\xi^{1-n}\left(1+q\right)\left[2\csc^2\theta - (1-q)\right]}{2a_*\left(1-\beta\right)} \sqrt{\frac{1 + a_*^2 \chi_{ms}^{-4} \xi^{-2} + 2a_*^2 \chi_{ms}^{-6} \xi^{-3}}{1 + a_*^2 \chi_{ms}^{-4} + 2a_*^2 \chi_{ms}^{-6}}}. \tag{20}$$

Since the poloidal length of the closed field line L can be estimated approximately as half of the circumference with diameter D, we have

$$L = AD = A \int_{r_H}^{r} (g_{rr})^{1/2}\, dr, \tag{21}$$

where D is the proper distance from the horizon to the place of disk where the closed field line penetrates, and $A \approx 0.5\pi$ is taken. The metric parameter g_{rr} is expressed as

$$g_{rr} = \rho^2/\Delta = \frac{r^2}{r^2 + a^2 - 2Mr} = \frac{\xi^2 \chi_{ms}^4}{\xi^2 \chi_{ms}^4 + a_*^2 - 2\xi \chi_{ms}^2}. \tag{22}$$

Incorporating equations (12), (21) and (22), we have

$$L/(2\pi\varpi_D) = \frac{A/2\pi}{\xi\sqrt{1 + a_*^2 \xi^{-2}\chi_{ms}^{-4} + 2a_*^2 \xi^{-3}\chi_{ms}^{-6}}} \int_{\xi_H}^{\xi} \frac{d\xi}{\sqrt{1 + a_*^2 \xi^{-2}\chi_{ms}^{-4} - 2\xi^{-1}\chi_{ms}^{-2}}}, \tag{23}$$

where $\xi_H \equiv r_H/r_{ms} = (1+q)/\chi_{ms}^2$. Therefore equations (19), (20) and (23) consist of the criterion of the screw instability in our model.

Inspecting the criterion (11), we find that the screw instability may occur, if the ratio of B_D^p to B_D^T is small enough. We can give an analysis before calculation. In fact, we find that B_D^T is proportional to ξ^{-1} approximately by combining equations (6), (8), (16) and (17). Thus the ratio B_D^p/B_D^T should be proportional to ξ^{1-n} by considering equation (1), and it is exactly the leading factor of the function $F(a_*; \xi, n)$. In addition, from equations (8), (16) and (17) we find that the larger value of the BH spin results in the larger values of j_D^p and B_D^T. Therefore we have the following conjectures on the screw instability.

(1) The screw instability would occur at some place far away from the inner edge of the disk.

(2) The screw instability would occur, provided that the BH spin a_* and the power-law index n are greater than some critical values.

The above conjectures are verified by the calculations on the criterion (19) as shown in Figure 3.

In Figure 3a $(2\pi\varpi_D/L)\, F(a_*; \xi, n) < 1$ holds for $0.8903 < a_* < 1$ with $n = 4$, and in Figure 3b it holds for $n > 3.34$ with $a_* = 0.998$. These results imply that the screw instability occurs, if the BH spin and the power-law index are greater than some critical values.

3.2. Screw Instability and CEBZMC

In WMLY we argued that the state of CEBZMC will occur, if the parameters a_* and n are greater than some critical values. So it is tempting for us to discuss the correlation of the screw instability with CEBZMC. Based on WMLY and the criterion (19) we have the critical line for CEBZMC and the critical lines for the screw instability in the parameter space consisting of a_* and n as shown in Figure 4.

From Figure 4 we obtain the following results.

(1) There is very little difference among the critical lines for the screw instability with different values of the factor A, and these critical lines can not be distinguished in Figure 4a, and are very near to the critical line for CEBZMC (thick solid line) as shown in Figure 4b. Therefore, the screw instability is rather insensitive to the values of the factor A.

(2) It is shown in Figure 4b that the critical line for CEBZMC corresponds to the larger values of a_* and n than the critical lines for the screw instability. It implies that the state of CEBZMC always accompanies the screw instability.

3.3. Disk Region for Screw Instability

From the above discussion we conclude that the minimum radial coordinate ξ_{screw} for the screw instability can be determined by the following equation,

$$(2\pi\varpi_D/L)\,F\,(a_*;\xi_{screw},n)=1. \tag{24}$$

Equation (24) implies that the disk region for the screw instability is

$$\xi_{screw}<\xi<\infty. \tag{25}$$

By using the mapping relation (9) and equation (25), we obtain the corresponding angular region on the horizon as follows,

$$\theta_M<\theta<\theta_{screw}. \tag{26}$$

By using equations (19), (20) and (23) we have the contours of constant values of ξ_{screw} for the screw instability in the parameter space consisting of a_* and n as shown in Figure 5.

From Figure 5 we find that the screw instability could even take place in the inner region of the disk with a small value of ξ_{screw}, provided that a_* and n are great enough. Since the large values of a_* and n in the MC process are supported by the recent *XMM-Newton* observation for producing a very steep emissivity in the inner region of the disk (WLM, WMLY), these values imply not only CEBZMC, but also the screw instability.

4. SCREW INSTABILITY AND ENERGY EXTRACTION FROM A ROTATING BH

Gruzinov (1999) argued that the screw instability can be regarded as a new mechanism of extracting rotational energy from a BH. His argument is based on a model with a bunch of closed magnetic field lines connecting a Kerr BH with a disk. Compared with Gruzinov's model, the magnetic field in our model is axisymmetric, and the region of the screw instability is determined by equation (25) rather than is given at random.

Considering the energy released due to the screw instability, the total power of the magnetic extraction from the BH consists of the following three parts, i.e.,

$$P_{total} = P_{BZ} + P_{MC} + \bar{P}_{screw}, \tag{27}$$

where P_{BZ}, P_{MC} and $\bar{P}_{screw}$ are the BZ power, the MC power and the average power due to the screw instability, respectively. Incorporating the region for screw instability given by equation (26) with the expressions for the BZ and MC powers given in WXL, we have

$$P_{BZ}/P_0 = 2a_*^2 \int_0^{\theta_M} \frac{k\,(1-k)\sin^3\theta d\theta}{2-(1-q)\sin^2\theta}, \tag{28}$$

$$P_{MC}/P_0 = 2a_*^2 \int_{\theta_{screw}}^{\theta_L} \frac{\beta\,(1-\beta)\sin^3\theta d\theta}{2-(1-q)\sin^2\theta}, \tag{29}$$

and

$$\bar{P}_{screw}/P_0 = 2a_*^2 \int_{\theta_M}^{\theta_{screw}} \frac{\beta\,(1-\beta)\sin^3\theta d\theta}{2-(1-q)\sin^2\theta}. \tag{30}$$

where $P_0 = (B_H^p)^2 M^2 \approx B_4^2 (M/M_\odot)^2 \times 6.59 \times 10^{28} erg \cdot s^{-1}$.

By using equations (28)—(30) we obtain the curves of P_{BZ}/P_0, P_{MC}/P_0 and $\bar{P}_{screw}/P_0$ varying with the parameters a_* and n as shown in Figures 6 and 7, respectively. Defining the ratio of $\bar{P}_{screw}$ to the total power P_{total} as $\eta_P \equiv \bar{P}_{screw}/P_{total}$, we have the curves of η_P varying with a_* and n as shown in Figure 8. In the following calculation $A = 0.5\pi$ is assumed.

From Figures 6, 7 and 8 we obtain the following results:

(1) For the given value of n, P_{BZ}, P_{MC} and $\bar{P}_{screw}$ all vary non-monotonically with the BH spin a_*, attaining the maxima as a_* approaching unity.

(2) For the given value of a_*, P_{BZ} increases monotonically, P_{MC} decreases monotonically , while $\bar{P}_{screw}$ varies non-monotonically with the power-law index n.

(3) The average power $\bar{P}_{screw}$ is always less than P_{MC}, and it is less than P_{BZ} in most cases, except that the power-law index is small as shown in Figure 7a.

(4) The ratio of power, η_P, increases monotonically with a_*, while it varies non-monotonically with the power-law index n, attaining its maximum $\eta_P \approx 0.084$ at $n \approx 5.25$ with $a_* \approx 0.997$.

Therefore we conclude that the screw instability contributes only a small fraction of magnetic extraction of energy from a rotating BH.

5. SUMMARY

In this paper the screw instability of the magnetic field connecting a rotating BH with its surrounding disk is discussed in the simplified model of CEBZMC. In our model the configuration of the poloidal component of the magnetic field is assumed, which remains constant on the horizon, and varies with the

radial coordinate on the disk according to a power law. By using an equivalent circuit for CZBZMC, we can calculate the poloidal current on the horizon and the disk, and then the toroidal component of the magnetic field on the disk is derived by using Ampere's law. Therefore, the criterion of the screw instability in our model is derived based on the Kruskal-Shafranov criterion.

Although the discussion is carried out under some simplified assumptions, several interesting results for the screw instability have been obtained.

(1) It is shown that the BH spin a_* and the power-law index n are involved in the criterion, and the screw instability will occur if the two parameters are greater than some critical values. This result means that the screw instability is apt to take place for a disk containing a fast-spinning BH, and has the magnetic field concentrating in the inner region.

(2) We find that the disk region for the screw instability can be also determined by a_* and n by virtue of the criterion, and the screw instability is apt to take place outside some critical radius on the disk.

(3) We prove that the state of CEBZMC always accompanies the screw instability as shown in the parameter space consisting of a_* and n.

(4) As an energy mechanism the effect of the screw instability on the magnetic extraction is discussed. It turns out that the contribution of the screw instability is not significant in our model of CEBZMC.

In this paper we fail to discuss the screw instability of the magnetic field in the BZ process, since we know very few about the remote astrophysical load. Considering stringent upper bound to the BZ power due to the screw instability in the BZ process (Li 2000a), we should give an overall evaluation on the effects of the screw instability on energy extraction from a rotating BH in the future work.

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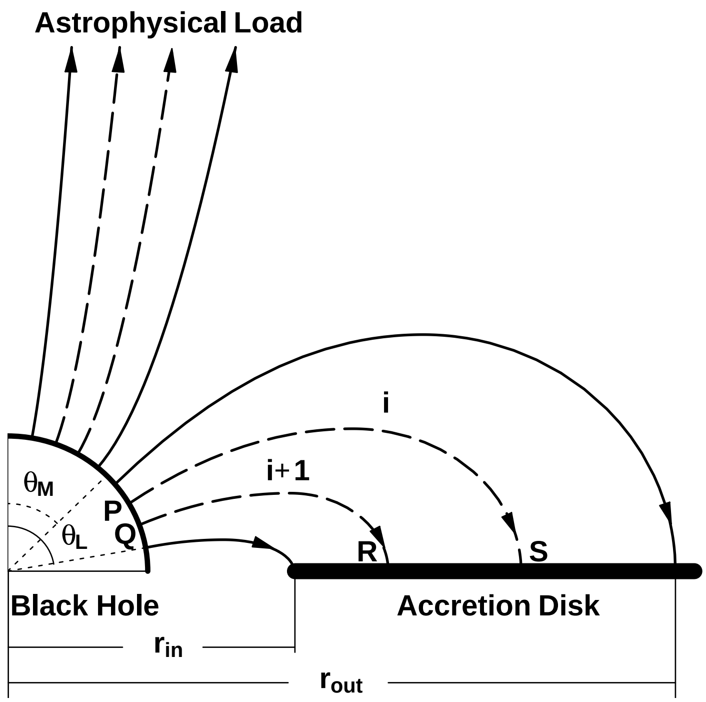

Fig. 1.— Poloidal magnetic field connecting a rotating BH with a remote astrophysical load and the surrounding disk.

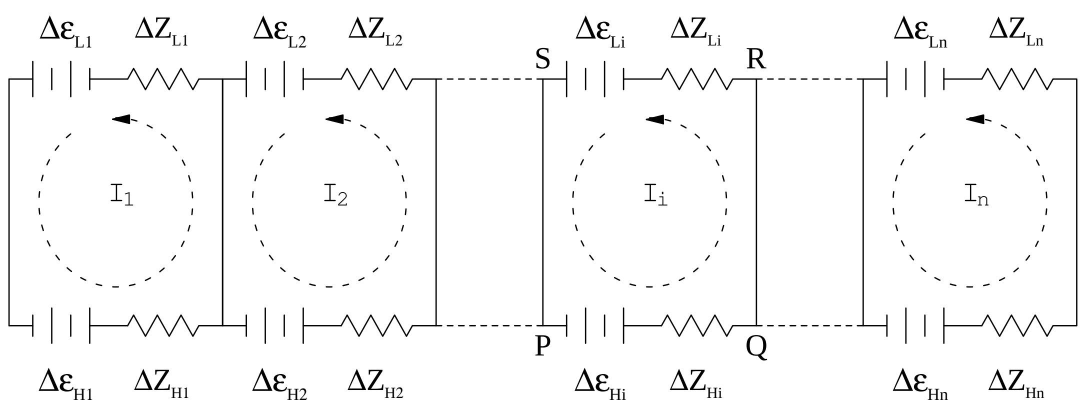

Fig. 2.— Equivalent circuit for a model of CEBZMC.

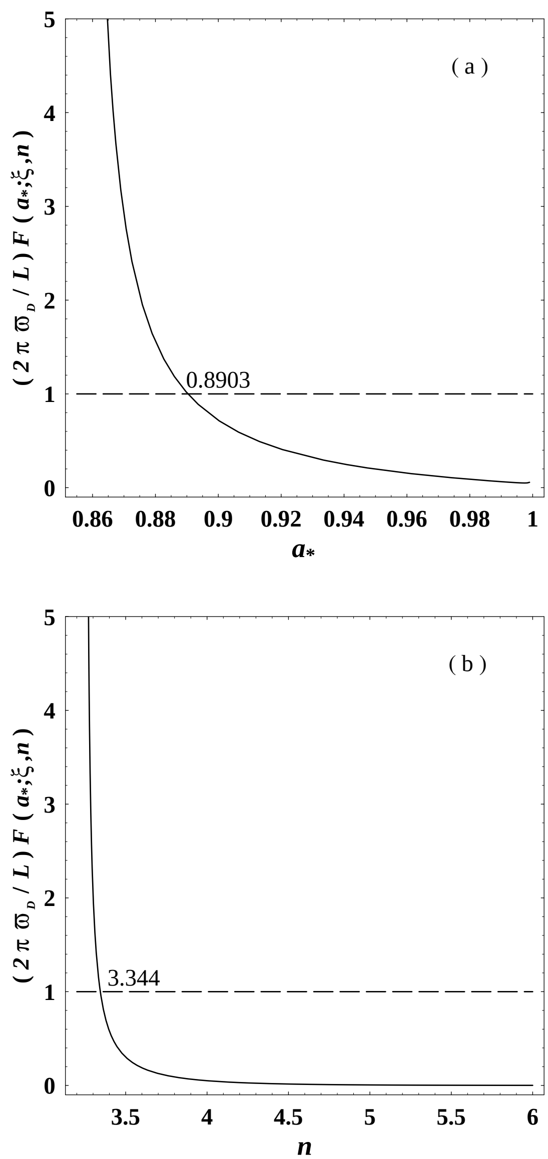

Fig. 3.— Value of $(2\pi\varpi_D/L)F(a_*;\xi,n)$ at $\xi = 5$ (a) varying with a_* for $n = 4$ (b) varying with n for $a_* = 0.998$.

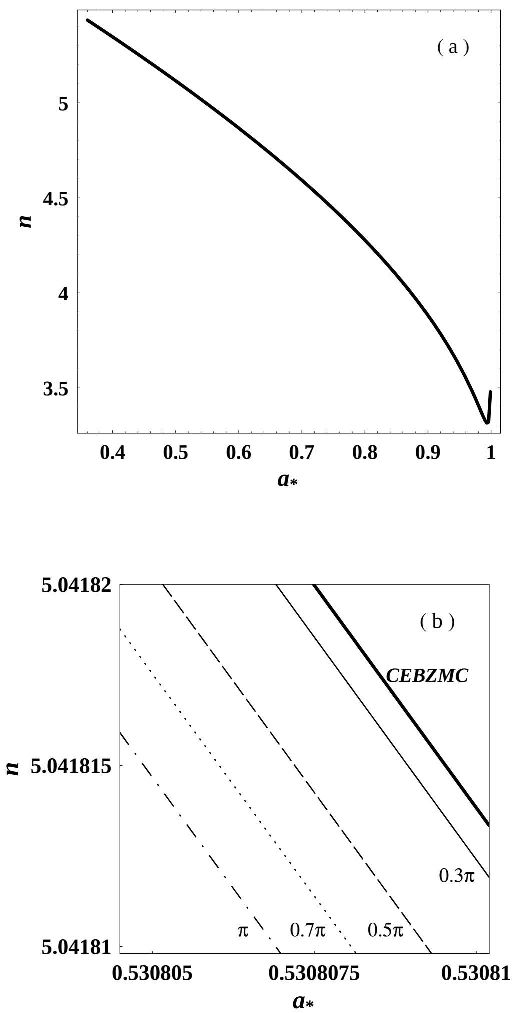

Fig. 4.— Critical line for CEBZMC (thick solid line) and critical lines for screw instability with different values of factor $A = 0.3\pi$, 0.5π, 0.7π,π in solid, dashed, dotted and dot-dashed lines, respectively.

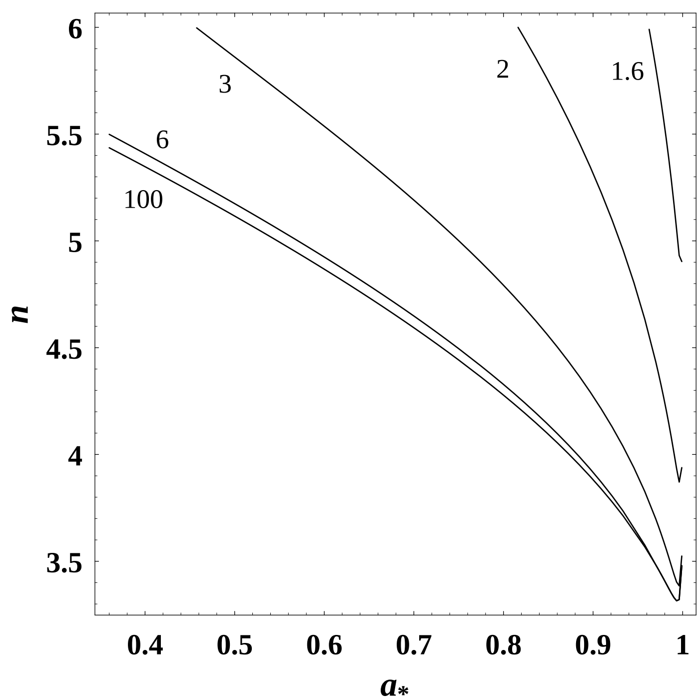

Fig. 5.— Contours of constant values of ξ_{screw} for the screw instability with $A = 0.5\pi$.

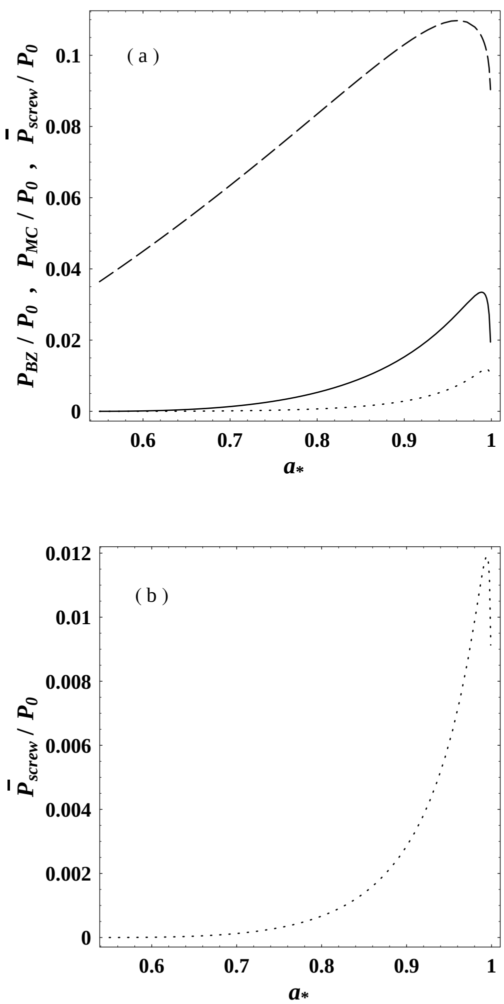

Fig. 6.— (a) Curves of P_{BZ}/P_0(solid line),P_{MC}/P_0(dashed line), and $\bar{P}_{screw}/P_0$ (dotted line), and (b) curve of $\bar{P}_{screw}/P_0$ (dotted line) varying with a_* for $n = 5$.

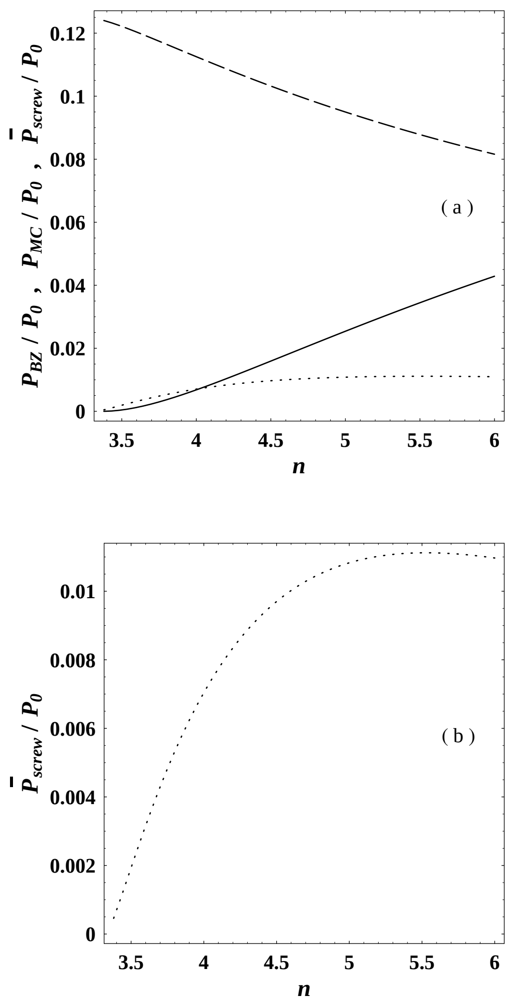

Fig. 7.— (a) Curves of P_{BZ}/P_0(solid line),P_{MC}/P_0(dashed line), and $\bar{P}_{screw}/P_0$ (dotted line), and (b) curve of $\bar{P}_{screw}/P_0$ (dotted line) varying with n for $a_* = 0.998$.

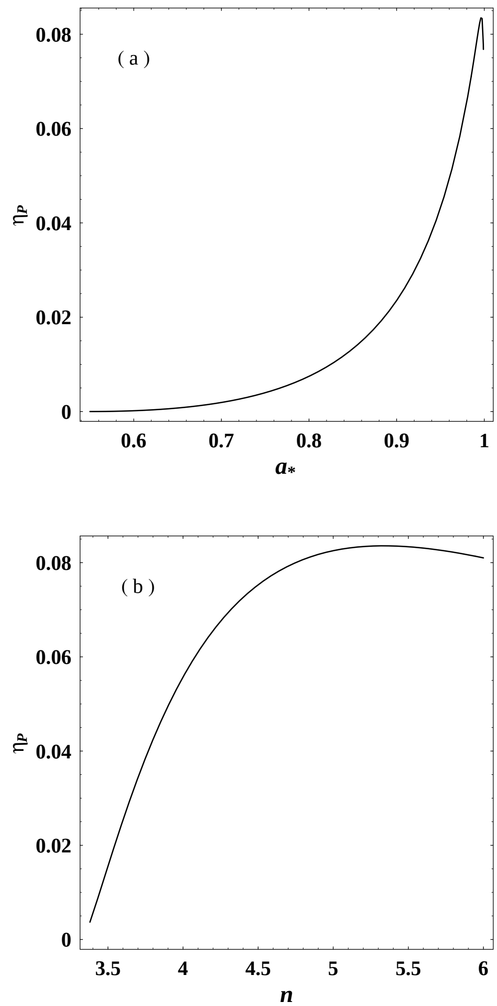

Fig. 8.— Ratio of $\bar{P}_{screw}$ to total power P_{total} (a) varying with a_* for $n = 5$, (b) varying with n for $a_* = 0.998$.